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The study and use of Al-based III-V native oxide in quantum well heterostructure (QWH) devices has been pioneered in this project, and since the time of its introduction (1990) has grown into an international activity. An almost all-oxide enclosed microcavity laser and LED have been realized in the latter stages of this project. By employing a tunnel junction contact as a mechanism to invert lateral (edgewise) electron current into injection hole current (and thus accomplish laterally offset carrier injection), we have demonstrated oxide-confined edge emitter and vertical cavity surface emitting lasers (VCSELs) driven entirely with lateral electron currents, and thus with reduced resistive losses in spite of the offset current source. This is potentially important for optoelectronic IC development. The use of the Al-based III-IV native oxide to thwart hydrolyzation and increase device reliability has been demonstrated.

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NATIVE-OXIDE-DEFINED SEMICONDUCTOR QUANTUM WELL LASERS AND OPTOELECTRONIC DEVICES: Al-BASED III-V NATIVE OXIDES

N. Holonyak, Jr.

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Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

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ABSTRACT

The study and use of the Al-based III-V native oxide in quantum well heterostructure (QWH) devices has been pioneered in this project, and since the time of its introduction (1990) has grown into an international activity. An almost all-oxide enclosed microcavity laser and LED have been realized in the latter stages of this project. By employing a tunnel junction contact as a mechanism to invert lateral (edgewise) electron current into injection hole current (and thus accomplish laterally offset carrier injection), we have demonstrated oxide-confined edge emitter and vertical cavity surface emitting lasers (VCSELs) driven entirely with lateral electron currents, and thus with reduced resistive losses in spite of the offset current source. This is potentially important for optoelectronic IC development. The use of the Al-based III-V native oxide to thwart hydrolyzation and increase device reliability has been demonstrated.

I. INTRODUCTION

Over the years this project has been the source of many developments in quantum well (QW) lasers, including (besides the coining of the "QW" name): (1) the first construction of a p-n diode QW laser (1977); (2) the first continuous room temperature operation of a QW laser (1978); (3) the discovery of impurity-induced layer disordering (IILD) of QW heterostructures and the use of IILD in defining the geometry of QW lasers and waveguides (1980), which was patented and now is widely used in industry; (4) the discovery of the Al-based III-V native oxide and its use in defining QW lasers and waveguides (1990), which also was patented and is now coming into wide use in industry; and (5) the introduction of offset tunnel junction contacts to minimize the hole conduction path (distance) in low-mobility p-type crystal and thereby make possible high-mobility lateral electron current biasing of fully oxide enclosed (compact) vertical cavity surface emitting lasers (VCSELs). Note that the buried oxide aperture that now is so important in VCSELs comes from this project, first being demonstrated on edge emitters. The last two developments listed above (the Al-based III-V native oxide and the offset tunnel junction contact) have generated 13 issued patents. The last patent concerns the offset tunnel contact that makes possible all-electron-current lateral biasing of lasers . These patents are listed at the end of this report, as well as a representative list of some of the papers leading to the patents.

II. Al-BASED III-V OXIDE TECHNOLOGY

The basic Al-based III-V native-oxide technology generated in this project is described by the patents of Refs. 1, 4, 8, 9, 10, and 12, and by the papers of Refs. 14, 17, 22, 24, and 27 (and to some further extent in all the other patents and papers listed).

III. Al-BASED III-V NATIVE OXIDE PROPERTIES AND DEVICES

The first devices demonstrated via the use of the Al-based III-V native oxide were various forms of stripe QW lasers (see Refs. 15, 16, and 18). These have included the generalization from the use of the prototype oxidizable ternary $Al_xGa_{1-x}As$ to the higher gap visible-spectrum quaternary $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ (Refs. 19, 20, 21, 22, and 28). In other words, we established very early in this work the importance of the oxidizable component Al in the III-V to be oxidized. We also showed very early that the III-V oxidation procedure could be important in improving crystal and device reliability (Refs. 17, 28, and 33).

From the very beginning (1990, Ref. 14) we established that the formation of the Al-based III-V native oxide is highly sensitive to the Al concentration and hence has the special capability of being formable as a buried oxide. A buried III-V layer with a sufficient Al concentration can be oxidized edgewise, and thus can be buried sandwiched between lower Al composition layers. The buried oxide is unique and makes possible unique applications, one being a simple form of higher reliability so-called window laser, e.g., as described in Refs. 21 and 25. In fact, in certain circumstances native oxide current-blocking windows can be formed on a finished (already processed) QW laser

(Ref. 25), just as for certain light emitting devices the reliability can be enhanced by, surprisingly, oxidation of the finished device (Refs. 8 and 28).

One of the more important uses of the buried oxide introduced in this project, and now used world-wide, is the oxide aperture used to define the current and the electromagnetic field in a QW laser. We demonstrated this use of the buried oxide on edge-emitter QW lasers (Ref. 23), and a year later it was picked up by VCSEL researchers. It owes its existence to the work of this project and now has become the preferred way of constructing VCSELs.

Because the Al-based III-V native oxide is very sensitive in its formation to the Al composition, and thus has the important property that it can be formed edgewise as a buried oxide, in fact, even as a stack of buried oxide layers, the oxide can be employed as one of the component layers of distributed Bragg reflectors (DBR) of VCSELs, either photopumped (Ref. 26) or current-driven devices (Refs. 30 and 31). It is worth mentioning that it is the buried form of the oxide that represents the only case of the Al-based III-V oxide that has been adequate to demonstrate field effect transistor operation (Ref. 27). Thus far, however, the Al-based III-V native oxide has been most successful in defining the geometry of optoelectronic devices, for example, lasers, waveguides, and LEDs, and has been less successful in field effect device applications.

IV. CONCLUSIONS

In the 10 years since the pioneering introduction of the Al-based III-V native oxide in optoelectronics in this project, not only have we been responsible for 13 patents (a half-dozen fundamental and controlling quite broadly the use of the oxide) and 60 or

more journal articles, a dozen Ph.D. students have finished their research in this area of work and are employed in optoelectronics R & D (oxide included) in industry. The journal literature indicates many more individuals and laboratories are working on the further study and exploitation of the Urbana Al-based III-V native oxide, which is rapidly becoming an important III-V semiconductor optoelectronics technology (including for IC purposes).

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